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ZERO-GRAVITY VORTEX VENT AND PVT GAGING SYSTEM

M. G. Downey and J. T. Trevathan
NASA Johnson Space Center
Houston, Texas

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ABSTRACT

Space Station and satellite reservicing will require the ability to vent gas on orbit from liquid supply or storage tanks and to gage liquid quantity under microgravity conditions.

In zero gravity, (zero-g) the vortex vent is capable of venting gas from a tank of liquid containing gas randomly distributed as bubbles. The concept uses a spinning impeller to create centrifugal force inside a vortex tube within a tank. This creates a gas pocket and forces the liquid through a venturi and back into the tank. Gas is then vented from the gas pocket through a liquid detector and then out through an exhaust port. If the liquid detector senses liquid in the vent line, the fluid is directed to the low-pressure port on the venturi and is returned to the tank. The advantages of this system is that it has no rotating seals and is compatible with most corrosive and cryogenic fluids. A prototype was designed and built at the NASA Johnson Space Center and flown on the KC-135 zero-g aircraft. During these test flights, where microgravity conditions are obtained for up to 30 sec, the prototype demonstrated that less than 0.10 percent of the volume of fluid vented was liquid when the tank was half full of liquid.

The pressure volume temperature (PVT) gaging system is used in conjunction with the vortex vent to calculate the amount of liquid remaining in a tank under microgravity conditions. The PVT gaging system is used in conjunction with the vortex vent to gage liquid quantity in zero or low gravity. The system consists of a gas compressor, accumulator, and temperature and pressure instrumentation. To measure the liquid in a tank a small amount of gas is vented from the tank to the compressor and compressed into the accumulator. Pressure and temperature in the tank and accumulator are measured before and after the gas transfer occurs. Knowing the total volume of the tank, the volume of the accumulator, the volume of the intermediate lines, and initial and final pressures and temperatures, the mass of the gas leaving the tank is equated to the mass of the gas entering the accumulator. The volume of liquid remaining in the tank is calculated using the ideal gas law.

INTRODUCTION

Space Station and satellite fluid reservicing will require the ability to vent gas from liquid supply or storage tanks on orbit. The vortex vent is a device which can be attached to a tank which, by means of centrifugal force, will separate a gas from a liquid in zero-g. This paper describes a program where the zero-g vortex vent system was designed, built, and tested both in one gravity at the NASA Johnson Space Center and in zero-g onboard the NASA KC-135 zero-g aircraft. A PVT gaging system which works in conjunction with the vortex vent was also designed, built, and tested at the Johnson Space Center. The very successful results of the tests are discussed in detail as well as plans for future development.

TEST SYSTEM DESCRIPTIONS

VORTEX VENT SYSTEM DESCRIPTION

The vortex vent system vents only gas from a tank of randomly distributed liquid and gas in zero-g without cumbersome rotating devices within the tank.

The system, Fig. 1, contains a vortex tube with holes along its length; the tube runs down the center inside the tank and has a pump impeller at one end. The impeller causes a vortex to form in the vortex tube, and pumps the primary two-phase flow from the tank through the holes into the vortex tube, through a venturi, and back to the tank.

The venturi suction port pumps a secondary flow path from the center of the impeller, after passing through holes in some rotating baffle plates, through a tube in the hollow shaft of the pump rotor, through a liquid detector and a 3-way valve (through the normally open port). The liquid sensor is wired to a vent/pressure controller which opens the 3-way valve to the vent position if the liquid detector indicates gas and the controller reads a tank pressure higher than the desired vented pressure. The vent pressure can be set on the controller or the 3-way valve can be operated manually.

The impeller is powered by an encapsulated permanent magnet rotor located within a sealed can. The rotor is driven by a rotating electrical field from a stator located around the sealed can. A Swagelok fitting is welded to the back of the can with a hole drilled through the can in the center of the fittings flow path. A .635 cm (1/4-in.) vent tube is located in the center of the hollow shaft of the rotor and through the fitting on the can. This arrangement eliminates drive shaft seals, a possible source of leakage. The hollow shaft of the rotor also provides a flow path for the working fluid acting as coolant and lubricant. The liquid travels around the outside of the rotor, which is a high-pressure area due to the impeller, around the carbon bearings, and back through the rear end of the hollow shaft of the canned rotor.

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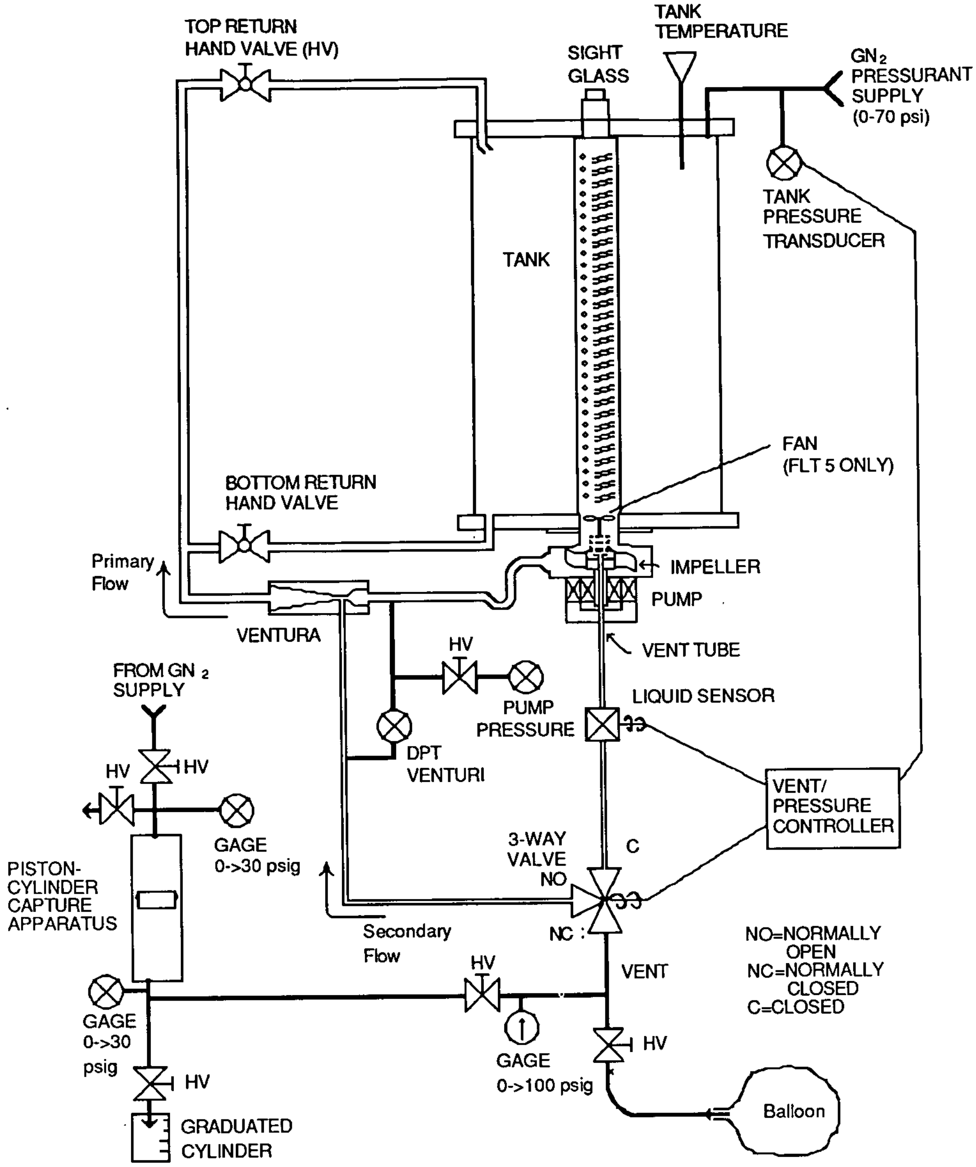

Fig. 1. Vortex Vent System.

System pressurization is accomplished with a GN_2 K-bottle. The tank operating pressure range is from 583.8 kPa (70 psig) down to the KC-135 cabin pressure (84.1kPa (12.2 psia)).

The tank is constructed of a cylindrical section of 31.75 cm (12.5-in.) inside diameter, clear acrylic tubing 45.72 cm (18 in.) long, sandwiched between two 43.18-cm (17-in.) diameter, aluminum, blind pipe flanges. All tank penetrations are machined into the aluminum flanges. The liquid level sensor is mounted in a cylindrical acrylic block. Sections of acrylic tubing are added to the primary and secondary flow paths to aid in observation of one and zero-g performance.

Water storage tanks for supplying different water levels, and a piston inside a clear cylinder with graduations for capturing and measuring the gas and liquid volume vented, are added for the flight-testing phase. A graduated cylinder is used to measure the liquid portion vented.

PVT GAGING SYSTEM DESCRIPTION

The zero-g PVT gaging system is designed to determine the quantity of liquid remaining in a tank in zero-g. The system consists of a gas compressor, accumulator, and temperature and pressure instrumentation. To measure the liquid in a tank, a small amount of gas is vented from the tank to the compressor and compressed into the accumulator. Pressure and temperature in the tank, and accumulator are measured before and after the gas transfer occurs. Knowing the total volume of the tank, the

volume of the accumulator, the volume of the intermediate lines, and initial and final pressures and temperatures, the mass of the gas leaving the tank is equated to the mass of the gas entering the accumulator. The volume of liquid remaining in the tank is calculated using the ideal gas law. The high-pressure gas in the accumulator is vented back to the tank, thus completing the closed loop.

DISCUSSION OF RESULTS

VORTEX VENT SYSTEM RESULTS

Ground Testing. Tests were performed on various tank positions, vortex tube configurations, vent tube inlet positions, and vent tube inlet configurations. Two primary flow return paths were also used.

Ground testing was performed with the vent tank in three positions relative to the gravity field. It was found that the vertical tank position with the pump at the bottom was best for test purposes. The flow in this position closely resembles the flow observed in zero-g aboard the KC-13 zero-g aircraft.

When the pump impeller started in this position, a rotating vortex of liquid would form along the walls with a gas column in the center of the vortex tube. A two-phase primary flow and a single-phase (gas only) secondary flow were observed. When venting was initiated, a small amount of liquid did get drawn into the vent tube, some of which was recirculated back to the tank by means of the vent/pressure controller.

Four vortex tubes were manufactured and tested in ground tests; the tube which created the best vortex was chosen for the flight tests.

Although good separation occurred during ground testing, most of the ground test data has limited use due to the change in flow patterns which occur in zero-g.

Flight Testing. In December 1986, 4 flight tests were conducted on 4 consecutive days for a total of 67 usable parabolas on the zero-g vent. In April 1987, a fifth flight test was conducted, providing 28 parabolas. Each parabola was good for about 15 to 25 sec of approximately zero-g. The 15- to 25-sec period of zero-g was between two periods of 1.8 g's. Accelerometer readings in the Z-axis showed actual forces between -.16 and +.12 g's. The 15- to 25-sec period of zero-g was preceded by a sharp drop-off from 1.8 g's and followed by a gradual increase to 1.8 g's.

For the first 4 flights, a vortex tube was used with 3 rows of 84 holes perpendicular to the tube wall, .318 cm (.125 in.) in diameter and about .508 cm (.2 in.) apart for a total inlet area of 19.94 cm^2 (3.09 $in.^2$). Prior to the fifth flight, the system was changed to use a vortex tube with tangent holes angled toward the pump. Modifications to other components will be described in the following discussion.

On the first parabola of the first flight, it was obvious that no venting would occur automatically when commanded. Typically, what would happen is the pump would pump out all the liquid near it and create a vortex in the tube, then when a gas pocket hit the impeller, flow would stop or nearly stop on the primary flow, causing the liquid in the secondary flow loop to stall also. The liquid detector would still detect liquid and no venting would occur. Manual override of the liquid detector inhibit, to open the vent valve, was thus initiated and used during the rest of the flight tests. Performance data includes the liquid vented as a result of this action. On flight 5, a fan blade was added to the impeller (Fig. 1) which prevented the primary and the secondary flow from stalling when the impeller encountered a gas pocket, thus not clearing the liquid from the secondary loop. A manual override was needed for only 2 of the 10 venting runs on flight 5 as opposed to 66 of the 67 parabolas on the first 4 flights. It is believed the two remaining flight 5 runs would also have cleared, given enough time.

When the zero-g portion of each parabola was encountered, the liquid would reposition in the tank due to the pump and capillary forces becoming dominant and the gravity forces becoming very small. This shift in liquid movement would tend toward, but would never completely reach, equilibrium during the short 15 to 25 sec of zero-g. A longer period of zero-g would have yielded better results.

Three vent tube inlet configurations were used during flight testing. During the first and second flights, an open .635 cm (1/4-in.) vent tube protruding 7.62 cm (3 in.) past the impeller into the vortex tube was used. The vent tube used on the third flight terminated even with the vortex tube end of the impeller, and included a liquid deflector on the pump side of the inlet tube to deflect bearing cooling circulation water away from the vent opening. The flight 3 configuration was used on the fourth flight, but with the addition of a rotating baffle plate on the vortex tube side of the vent tube. The fifth flight used the flight 4 configuration plus two additional rotating baffle plates and a perforated circumferential shield around the baffle plates.

The performance of each of the four-vent tube inlet configurations is shown in Fig. 2. Each point is an average of 1 to 4 points at the same condition. Due to the short duration of the zero-g environment and the variation of small g-forces, particularly in the Z-direction, the data has some scatter and is somewhat statistical in nature. Since test time in zero-g was severely limited, only general trends can be used from the data. Great improvement can be seen with the addition of the rotating baffle on the fourth flight (keeping in mind that the plot scale is semi-log). Less than 1 percent of the volume vented is liquid when the tank is vented with one-third or less liquid left in the tank. The volume of nitrogen gas vented is measured in standard liters, the standard conditions being 18.33°C (65°F) and 101.325 Pa. (14.7 psia). On the fifth flight, the greatest improvement can be seen with the increase of the three additional rotating baffle plates and circumferential shield. Less than one-tenth of 1 percent of the volume vented was liquid when the tank was one-half or less filled with liquid.

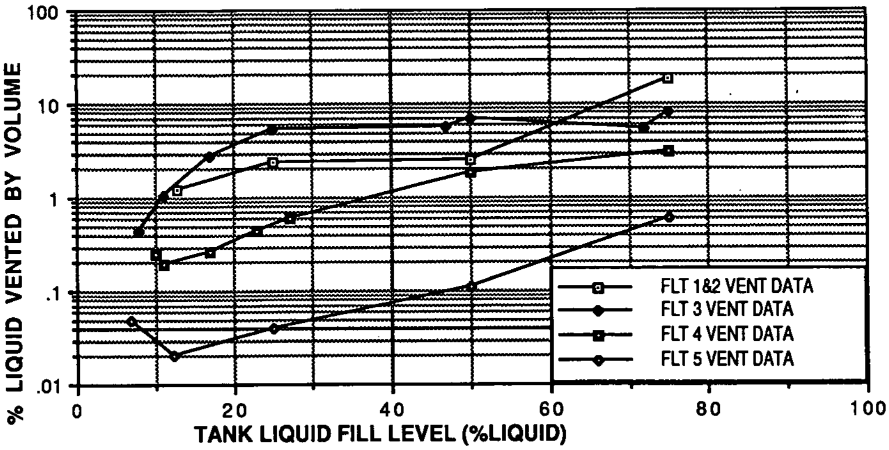

Fig. 2. Zero-gravity Vent Performance.

Another variable was the throttling of flow through the vent. The two-phase flow changed from slug flow to annular flow as the venting velocity decreased. Slug flow consists of alternating pockets of gas and liquid flowing through the line. Annular flow consists of a thin film of liquid flowing along the walls at a low velocity and gas in the center of the tube flowing at a higher velocity. During full throttle (full flow), the liquid detector did not respond fast enough to detect the liquid slugs and, thus, did not usually shut off the vent except when exposed to very long columns of liquid. Redesign of the detector or the flow path by the detector is necessary in order for it to function effectively after venting has started. The venting performance is neither increased nor decreased by throttling the vent port. When throttling was done to restrict, and thus slow down the flow, the annular flow formed and did not create a thick enough liquid fraction in the tube to trip the liquid detector. In future tests, a fluidic separator will be installed upstream of the liquid detector to feed it liquid only. Throttling the flow can then be used to adjust the performance of the second stage of separation.

GAGING RESULTS

Ground testing was performed using a hydraulic pump and piston/cylinders instead of a compact gas compressor due to difficulty in acquiring a compressor with a high enough compression ratio. Testing was performed with tank pressures of 721-790 k Pa. (90-100 psig) and ambient temperature. The liquid level in the tank was varied throughout testing. On performing the gaging, accumulator pressure rose to 6.99-8.37 MPa. (1000-1200 psig), and accumulator temperature rose to 37.7-48.9°C (100-120°F). Answers repeatable to ±1 percent have been achieved to date, but ultimate accuracy has yet to be achieved. This is believed to be at least partially due to the hydraulic losses and friction involved in the piston/cylinder mechanism. Further work to be done involves verifying the known volumes and integration with the zero-g vortex vent system, followed by more testing. Before actual implementation in a flight environment, a more compact system utilizing a gas compressor needs to be developed.

APPLICATIONS

VENTING

To reservice a tank with liquid, you must first vent the pressurant gas in order to bring the tank pressure low enough to transfer in new liquid. Four known methods of liquid expulsion are currently available for use in a zero-g environment. They are diaphragm, screen surface tension, super critical, and mechanical. Of these only the flexible diaphragm tank can be used for both liquid expulsion and also for venting gas during resupply. Efficient reliable flexible diaphragms are not available for all fluids. Those fluids that are cryogenic or highly corrosive will require a different method of liquid/gas separation. Mechanical means of separation in a storage tank have not been used thus far due to the complications of rotating fluid couplings. No method of venting gas only from a screen or super critical storage tank has been developed before. This leaves a gap in technology that the vortex vent can readily fill.

The vortex vent can be adapted to either the screen or supercritical tank. Operationally, the vortex vent can be used for resupplying the super critical tank by allowing the one-phase fluid to cross the two-phase boundary through normal consumption and then turning on the vortex vent to drop the pressure where new cryogenic fluids can be transferred into the storage tank. The screen tank would operate much the same way except it would not be necessary to drop the fluid to two phase since it is already in that state. Physical integration into either of these types of storage tanks is also simple. The only part which is actually in the tank is the vortex tube. About a 6.35 cm (2.5 in.) flanged opening at one end of the tank would be required in order to attach the vortex vent with the proper insertion of the vortex tube. A small return penetration is also required for the primary flow.

GAGING

Gaging in zero-g and zero acceleration has always been a difficult problem. Common means of measuring liquid quantity, such as dip sticks and float gages do not work in zero-g. The PVT gaging system can be used in conjunction with the vortex vent in order to fulfill the need of zero-g quantity gaging.